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COSMIC RAYS AND PLASMA EVENTS

IN THE GALAXY AND METAGALAXY

by

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SUMMARY

It is pointed out that the various instabilities (including, in the first place, the beam instability), taking place in the interstellar and intergalactic plasma, exert a substantial influence upon the distribution function of cosmic rays by directions and energies, and also on their spatial distribution and diffusion.

As a result of the above, the accounting of plasma events acquires a fundamental value in the astrophysics of cosmic rays and in the theory of their origin. In particular, the presence of instabilities must apparently lead to a rapid and practically total isotropization of cosmic rays in galaxies as well as in the intergalactic space. In the transitional region between strong and weak field, the outflowing cosmic rays with a strong field (either from galaxy or supernova shell) will lead to the development of turbulence, and by the same token to "self-locking". Discussed are also several other related questions.

* * *

In the course of the last years it has become already generally recognized that cosmic rays play a substantial dynamic and energetic role in galaxies, and more particularly in radiogalaxies. For example, in our Galaxy, which is a normal galaxy, the energy density of cosmic rays is $w_G \sim 10^{-12}$ erg/cm^{-3} and the magnetic field intensity is $H \sim 3 \div 10 \cdot 10^{-6}$ oe , so that

$$\frac{H^2}{8\pi} \sim w_G \; ;$$

the inner energy density of a gas with concentration $n \sim 1$ and temperature $T \sim 10^{4} {}^{\circ}K$ is $\varepsilon \sim n\,T$ and, therefore, in most of the Galaxy regions $\varepsilon < w_G$.

Values w_g of energy density of cosmic rays, still by several orders greater, are encountered in radiogalaxies. Moreover, there exist specific data on the spectrum and spatial distribution of cosmic rays in galaxies (for details see [1] and the references indicated there).

In case of metagalactic space the situation is already different: here even such basic question as mean energy density of cosmic rays, w_{mg}, is the object of discussion. Thus, in our opinion [1, 2] (and the same conclusion is also found in other works)

$$w_{mg} \ll w_G \sim 10^{-12} \text{ erg/cm}^3 \qquad (1)$$

and, for example, $w_{mg} \leq 10^{-15}$ erg cm^{-3}.

To the contrary, Burbidge and Hoyle are inclined to believe in their work [3], and still more specifically in preceding papers, that $w_{mg} \sim 10^{-12}$. We shall not, however, pause here at concrete objections [4] provoked by the estimates of [3], inasmuch as there is little more that we could add to the already presented ideas in favor of validity of the inequality (1) [1, 2]. If this inequality is fulfilled and, at the same time, the metagalactic cosmic rays are to a sufficient measure isotropic, they can not significantly contribute to w_G [1, 2], that is, the main part of cosmic rays in the Galaxy must also form in it. In this connection it is important to ascertain the acceptable degree of anisotropy of cosmic rays in the Meta-galaxy; incidentally, the question of isotropy (its nature and the possible degree of anisotropy) is quite important and not sufficiently clear at all even when applied to the Galaxy.

The opinion was voiced in [1, 2] (in particular with respect to the work by Sciama (5]), that no somewhat substantial anisotropy of cosmic rays may exist in the metagalactic space, inasmuch as the magnetic field (in any case so long as $w_{mg} > \frac{H^2}{8\pi}$) is incapable of compensating the anisotropic pressure of cosmic rays. However, such a conclusion has not been strenghtened by concrete estimates, while Pikel'ner [6] recently proposed a model of a regulated metagalactic field in which the assumption of cosmic ray flux's anisotropy appears to be quite admissible at first sight *.

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* [see infrapaginal comments in the following page]

Therefore, the question of anisotropy of cosmic rays was found to be quite essential. Aside from the enumerated problems of cosmic ray astrophysics, there is still the problem of transitional region from galactic to metagalactic space that should be referred to them. It should, in particular, be ascertained what the cosmic ray flux is in that region, and, generally speaking, in what fashion do these cosmic rays emerge from galaxies, what is the form of the spectrum of galactic cosmic rays in the region of low energies [1, 7] and, finally what is the role of cosmic rays from the standpoint of processes taking place in the metagalactic gas (there is namely question of heating of that gas).

Thus, the great achievements reached in the region of astrophysics of cosmic rays in the course of the last decade cannot in any way shield the presence of actual and, at the same time, nebulous moments of time.

The understanding and the further investigation of the enumerated insufficiently clear problems of astrophysics of cosmic rays is, in our opinion, closely linked with the accounting of plasma effects in cosmic space. Evidently, this assertion is sufficiently obvious in its general form; it is included in [1] and , probably also in a series of other sources. (We shall point out, in particular, the existence of analysis of a series of plasma effects in cosmic conditions, conducted by Tsytovich [8]). However, we refer here to entirely concrete remarks linked with the account of beam and other instabilities in a rarefied plasma (these questions were more than once discussed and still are in their general form, as well as in connection with the problem of thermonuclear synthesis, the theory of sporadic solar radio emission, the collapse of a magnetic star and so forth [9 — 14] **.

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* [from the preceding page]. - In such a model, just as in [?], cosmic rays, isotropic in the region with the field H_g (galaxy) enter the metagalactic space with a field $H_{mg} \ll H_g$ with the preservation of the adiabatic invariant $\sin^2 \Theta / H$. That is why in the Metagalaxy cosmic rays are strongly anisotropic ($\Theta_{max} = \sqrt{H_{mg}/H_g}$ and $w_{mg}/w_g \simeq H_{mg}/2H_g$). Here the Lewill theorem, according to which the intensity I of cosmic rays in a constant magnetic field is identical along particle trajectory, is taken into account. At $H_g \sim 3 \cdot 10^{-6}$, $H_{mg} \sim 3 \cdot 10^{-9}$ and $w_g \sim 10^{-12}$, hence $\Theta_{max} \sim 1°$ and $w_{mg} \sim 10^{-15}$ erg cm^{-3}. Thus, the inequality (1) is observed, but practically all the cosmic rays in the Galaxy might have a metagalactic origin.
** The basis of the present paper is the report contributed by the author to the International Symposium on the problem of multiple bodies (illegible).

To be specific, let us consider the following possibility : the magnetic field egresses from galaxy into the metagalactic space in a smooth fashion (expansion of the tube of force) and in the absence of any sort of field irregularities, wave fronts and so forth,

Under similar conditions the isotropic or quasi-isotropic cosmic rays will move with the preservation of the adiabatic invariant

$$\sin^2 \theta \, / \, H \; = const,$$

and, as already pointed out above, they will form in the Metagalaxy a beam moving practically along the field. But such a case is a classical example of what happens when beam instability develops. At the same time it is material that the plasma frequency of the "mother" (metagalactic) plasma and of the beam itself are very high when compared with $1/\tau_g$, where τ_g is the characteristic time of galaxy evolution or even the time of radiogalaxy explosion. In reality, making use of the well known expressions (see, for example, [15]) and without additional explanations, let us bring forth certain figures for the metagalactic plasma with electron concentration $n \sim 10^{-5}$.

In this case the plasma frequency is

$$\omega_o = \sqrt{\frac{4 \pi e^2 n}{m}} = 5.64 \cdot 10^4 \sqrt{n} \sim 10^2,$$

and the Debye radius

$$\mathcal{D} = \sqrt{\frac{\varkappa}{4 \pi e^2 n}} \simeq 5 \sqrt{\frac{T}{n}} \sim 5 \cdot 10^5 \; cm$$

(at temperature $T \sim 10^5 \, °K$).

Under the same conditions the number of collision of electrons with ions is

$$\gamma = \frac{5.5 \, n}{T^{3/2}} \, ln \, (220 \, T \, n^{-1/3}) \sim 10^{-11} \; sec^{-1}.$$

In the field $H_{mg} < 10^{-7}$ the gyrofrequency is $\omega_H = \frac{eH}{mc} = 1.76 \cdot 10^7 H < 10$ and therefore, $\omega_o^2 \gg \omega_H^2$. It is already clear from these figures that weakly-damping plasma waves ($k\mathcal{D} = \frac{2\pi}{\lambda}\mathcal{D} \ll 1$) can already propagate in the metagalactic space. Further, at spectrum invariability, the value $N_{KA} \sim 10^{-13}$ responding to density $w_{KA} \sim 10^{-15}$ erg/cm^3, even for a flux of cosmic rays with concentration $N_{KA} \sim 10^{-13}$ cm^{-3} the plasma frequency of the beam is

$$\omega_s = \sqrt{\frac{4\pi e^2 c^2 N_{KA}}{E}} \sim 5 \cdot 10^4 \sqrt{\frac{m N_{KA}}{M}} \sim 5 \cdot 10^{-4}$$

(here the total energy is $E \sim Mc^2 \sim 10^9$ ev, which responds to protons contributing principally to w_{KA}). The exceptional smallness of the ratio

$$\frac{\tau_s}{\tau_g} \sim \frac{2\pi}{\omega_s \tau_g} \sim \frac{10^4}{\tau_g}$$

is evident. It is naturally more material that the ratio $\frac{1}{\gamma \tau_g}$ is also small, where γ is the increment of plasma oscillations, setting in by the strength of beam instability. For the case under discussion the value of γ has recently been estimated by us in the paper [16], and precisely for the indicated parameter values and in the assumption that the scattering of velocities in the beam is $v_T \sim c$. At the same time $1/\gamma_{max} \sim 30$ years. The point is that $\gamma_{max} \sim \omega_s^2/\omega_o$, and at the same time the greatest increment responds to waves for which $kc \sim \omega_o$ (for the shortest, weakly-damping waves $kc \sim \omega_o$ or $k\mathcal{D} \sim 1$. which leads to the value

$$\gamma_{min} \sim \frac{\omega_s^2}{\omega_o} \cdot \frac{v_T^2}{c^2} \sim 10^{-4} \gamma_{max}, \quad \left(1/\gamma_{min} \sim 3 \cdot 10^5 \text{ years}\right).$$

When taking into account the magnetic field, the beam will also generate other-type waves, which at the first stage at least may only increase the accretion rate of perturbations in the plasma (incidentally, the beam instability does not amount to generation of longitudinal waves either [22] even in the absence of a magnetic field). Further, at galaxy, and particularly radiogalaxy boundary, one may expect concentrations by several order greater than the utilized metagalactic value $N_{KA} \sim 10^{-13}$.

However rough the indicated estimates may be, the "reserve" appears to be so great that we reach the conclusion of the impossibility of existence of somewhat prolonged time of strongly anisotropic distribution of cosmic rays. [* see infrapaginal note next page].

The beam instability leads first of all to wave intensity increase and then to plasma "turbulization" amd to the isotropization of the beam itself (in this regard the anisotropic instability, discussed below. and also other instability mechanisms are essential). The emitted and subsecuently absorbed waves as a result of collisions (and in a well known sense of non-linear processes also) lead to heating of the metagalactic medium. This important cuestion (particularly from the cosmological point of view) is examined in detail in [16], so that we shall not dwell upon it here any longer.

How far will the isotropization of cosmic rays go as a result of beam instability ? Had the distribution function (spectrum) of cosmic rays been invariable, one might have anticipated a drop of a certain effective concentration of particles with anisotropic distribution, $N_{KA, a}$ (degree of cosmic ray anisotropy $\delta \sim N_{KA, a}/N_{KA}$). to values, when $1/\gamma \sim \tau_g$. Inasmuch as $\gamma \, \omega \, N_{KA, a}$, even at $\tau_g \sim 10^6$ years, we obtain thereform a very small value $N_{KA, a} \sim 1C^{-17}$. Another effect is evidently more essential — the variation of the very distribution of particles in the beam with "plateau" formation (as is well known, in the one-dimensional case, the beam is unstable only in the presence in its spectrum by velocities of a certain maximum at $V \neq 0$). As a result of this, so long as their flux is anisotropic*, the maximum in the spectrum of cosmic rays will shift further and further into the region of low energies. But in this region the ionization losses rise sharply and therefore a cause is available for maximum preservation. Thus, the beam instability must lead to effective isotropization of cosmic rays ** and the shift of the maximum in their spectrum toward the region of low energies. This is precisely what is observed, that is, the anisotropy of cosmic rays is generally not relaibly established and it does not, in any case, exceed fractions of a percent (see [1]).

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* [from the preceding page].- We shall not touch here upon the subject of cosmic rays of solar origin, inasmuch as in that case fast processes are essential. But the accounting of observations, made in this paper, is obviously necessary even at analysis of the problem of solar cosmic rays.

* For isotropic distribution of particles by directions the presence of maximum in the spectrum does not lead to instability [17].

**. As communicated to the present author, the same conclusion was reached by V. N. Tsytovich [see infrapaginal note end page for further long-hand remarks made by the present author at correction]

As to the maximum of cosmic ray spectrum observed near the Earth,
it may be fully explained by the action of the Sun and of the solar
system [1, 7]. In the light of the above-said, it would be neccesary to
explain the presence of anisotropy and maximum, had they been revealed,
rather than the presence of isotropy and the absence of a maximum in
the spectrum of galactic cosmic rays.

The beam instability of the flux of cosmic rays, leaving the
galaxy, must quickly distort the regular pattern of field's tubes of
force expansion, which we took as a basis. Moreover, under conditions
of such expanding tube of force there must arise an aperiodical aniso-
tropic instability leading to distortion, and, as a matter of fact, of
turbulzation of the magnetic field [10,18]. The criterion of such an
instability has the form

$$w_{KA,\parallel} - \frac{1}{2} w_{KA,\perp} \quad \frac{H^2}{8\pi},$$

where $\quad w_{KA,\parallel} = \frac{MN_{KA} \, \overline{v_\parallel^2}}{2} \quad , \quad w_{KA,\perp} = \frac{MN_{KA} \, \overline{v_\perp^2}}{2}, \quad v_\parallel$ and $v_\perp$ being res-

pectively the velocity components of cosmic rays, parallel and perpendi-
cular to the field (we make use of a nonrelativistic expression, which
can hardly lead to a notable error, inasmuch as for the main part of
cosmic rays $E - Mc^2 \lesssim Mc^2$). As has been shown, at particle passage
from Galaxy to Metagalaxy* $w_{KA,\parallel} \simeq w_{mg} \gg w_{KA,\perp}$, and, at the same time,

$$w_{mg} \simeq \frac{H_{mg}}{2 H_G} w_G \sim \frac{H_{mg} H_G}{16} \gg \frac{H_{mg}^2}{8\pi}.$$

Therefore, the criterion (2) will be fulfilled with a large "reserve"
(for example, at $H_{mg} \sim 3 \cdot 10^{-8}$ we have $w_{mg} \sim 3 \cdot 10^{-15}$ and $\frac{H_{mg}^2}{8} \sim$
$\sim 3 \cdot 10^{-17}$). The accretion increment of the discussed field perturba-
tions is

$$\gamma_a \sim \sqrt{\frac{w_{mg} - H^2/8\pi}{M N_{KA}}}, \quad \sim CK,$$

inasmuch as $w_{mg} \sim Mc^2 N_{KA}$. Further, the perturbation wavelength may

*with invariant $\frac{\sin^2\theta}{H}$ preservation.

exceed the gyroradius of cosmic rays

$$r_H \sim \frac{Mc^2}{eH} \sim \frac{3 \cdot 10^6}{H_{mg}} \sim 10^{14} cm \quad (\text{at } H_{mg} \sim 3 \cdot 10^{-8}).$$

Consequently,

$$\gamma_a \lesssim \frac{2\pi c}{r_H} \sim 10^{-3} \text{ and } 1/\gamma_{a,\,max} \sim 10^3 \text{ sec (!)}$$

It is therefore clear that if the beam of cosmic rays reached the meta-galactic region (region where $H \sim H_{mg} \sim 3 \cdot 10^{-8}$) without isotropization and without destruction of the regulated field structure, both these processes would take place very rapidly. But this means that the transitional regional must be forming factually; if in the galaxy the field was regular it will become turbulent in this region, while the cosmic ray flux will be isotropizing. By the same token, if a new great/portion of cosmic rays forms in any galaxy (say, as a result of explosion of the galactic nucleus), these cosmic rays will be rapidly "self-ioslating" — surrounding the region occupied by then by a turbulent layer, hindering the rapid outflow of cosmic rays in the surrounding space with a weak field. It is precisely for that reason, and from the discussed point of view that radio emitting clouds are observed in radiogalaxies, rather than a simple spreading of cosmic rays along the field lines. Quite evidently, the "clouds" referred to above, and containing cosmic rays, may expand and move as a whole, fact which is observed. Moreover, some diffusive outflow of cosmic rays is also possible in the presence of a turbulent boundary layer limiting the system (the Galaxy, the "clouds" in radiogalaxies and shells in supernovae). Unfortunately, without detailing the picture and the accounting of all essential instabilities, of nonlinear interaction of waves and so forth, no reliable estimate of the diffusion coefficient $\mathfrak{D}_{KA}$ is possible (see [11]). We may, apparently, consider the value

$$\mathfrak{D}_{KA,\,min} \sim \frac{c r_H}{3} \sim \frac{Mc^3}{3 e H} \sim \frac{3 \cdot 10^{16}}{H}$$

as the minimum value of $\mathfrak{D}_{KA}$ (having in mind particles with energy $E \sim Mc^2$). The thus obtained value $\mathfrak{D}_{KA,\,min} \sim 10^{22} cm^2 \cdot sec^{-1}$ (at $H_G \sim 3 \cdot 10^{-6}$) is significantly smaller than the coefficient $\mathfrak{D}_{KA} \sim 10^{28} - 10^{29}$ used in [1].

However, here there is still no contradiction, inasmuch as in the turbulent region is smaller than in the Galaxy as a whole, while the coefficient $\mathcal{D}_{K\Lambda}$ can still be substantially greater than $\mathcal{D}_{K\Lambda, min}$. At any rate, the appearance of the turbulent layer in the transitional region from a strong to a weak field constitutes unquestionably a favorable moment of time to explain the retention of cosmic rays in the shells of supernovae, in the Galaxy and in radio-emitting regions (clouds) of radiogalaxies.

From the above-expounded it follows also that cosmic rays entering the intergalactic space from galaxies must rapidly isotropize, and be practically isotropic in that very same space. By the same token, at observation of the inequality (1), the cosmic rays observed in the Galaxy must also be forming in it (here we are not concerned with particles of very high energy, which do not practically contribute at all to w_G). As follows from X-ray data, the temperature of the metagalactic gas is

$$T_{mg} < 3 + 5 \cdot 10^6 \, {}^\circ K \text{ (see [19, 20].}$$

At the same time, if cosmic rays arrived from galaxies in such an amount, that the value $w_{mg} \sim w_G \sim 10^{-12}$ be attained, one ought to expect a heating of metagalactic gas to a temperature $T \sim w_G / \varkappa n \sim 10^9 \, {}^\circ K$. By the same token we dispose of still another argument (besides those brought out in [1, 2, 21] in favor of validity of the inequality (1).

Summing up we may briefly assert that the accounting of plasma effects (and the question is here first of all about the instability of the anisotropic distribution of cosmic rays) is of basic importance for cosmic ray astrophysics (and in particular for the theory of their origin). It is true that the arguments brought out are in a series of cases insufficiently developed and one is rather led to speak in terms of a program of investigation and guessings than about proof. One should remember, however, that numerous essential parameters (for example, the intensity of the metagalactic magnetic field) are entirely unknown, and, therefore, even more precise calculations would have been as equally insufficiently convincing. However, such calculations are obviously indispensable and a series of possibilities are here available. Thus, as it appears to us,

a detailed and multilateral accounting of plasma events will emerge as
a new stage in the development of cosmic ray astrophysics.

**** T H E E N D ****

A D D E N D U M

Post-correction remark by the Author [refer to infrapaginal not of page 6]

At the same time, according to calculations by V.N.Tsytovich,
the isotropization of a relativistic beam in an isotropic plasma may be
found to be of little effectiveness when accounting the linear wave inter-
action. (See also [24]). On the other hand, the rate of isotropization
may considerably increase if the waves, excited in the plasma, are not
created by the considered beam, but by some other sources.

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* N. B.- References [23] and [24] are long-hand additions to the rest.

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